

1. Name of Experiment/Project/Collaboration: **Super-Kamiokande**

2. Physics Goals

Primary

- Maintain sensitivity to a gravitational collapse supernova anywhere in our galaxy. Such an event would result in thousands of neutrino interactions in a few seconds leading to bountiful studies not seen since SN1987A.
- Search for proton decay and bound neutron decay. Super-K already has the best limits on many modes; these continue to improve with more data and improved analysis techniques, and additional modes are being explored.
- Make precision measurements of neutrino oscillation parameters using atmospheric neutrinos. These measurements are to be scientifically compared and contrasted with those by accelerator experiments to potentially reveal new physics. Super-K also has sensitivity to τ neutrino appearance.
- Use atmospheric neutrinos to study non-standard neutrino physics. Due to great sensitivity to matter effects, a wide energy range from 100 MeV to 1 TeV, and a wide range of baselines, atmospheric neutrinos provide a valuable laboratory for testing exotic models including CPT violation, decoherence, and non-standard interactions (NSI).
- Continue the study of neutrino oscillation using solar neutrinos. Super-K has sensitivity to solar neutrino-electron scattering with high statistics and directionality. In combination with other solar and reactor data, Super-K data are providing precise parameter measurements.
- Search for diffuse relic supernova neutrinos. Super-K has the best limits to date and is continuing to improve background rejection. Addition of gadolinium to the detector is under study as a potential aid to background rejection. See section on R&D for future enhancements.
- Extend the search for indirect dark matter detection (via annihilation or decay in the Sun, Earth, galactic center, or halo) to medium to low WIMP mass. Currently, Super-Kamiokande has the best limits on indirect dark matter detection below the 100 GeV threshold of IceCube.

Secondary

- The Super-Kamiokande detector is the far detector for the T2K experiment.

1. Expected location of the experiment/project:

The detector is located in the Kamioka mine near Toyama, Japan.

2. Neutrino source:

The Super-K experiment is unique in that it works both in astroparticle physics, studying atmospheric, solar, supernova and, potentially, other astrophysical neutrinos, and with accelerators, as the far detector in the T2K long baseline beam.

3. Primary detector technology: **Water Cherenkov**

4. Short description of the detector : **The Super-K experiment is based on a 50-kton water Cherenkov detector with 11,146 50-inch inner detector and ~1900 8-inch outer detector photomultiplier tubes.**

5. List key publications and/or archive entries describing the project/experiment.

Evidence For Oscillation of Atmospheric Neutrinos. The Super-Kamiokande Collaboration: Y.Fukuda, et al. *Phys. Rev. Lett.* 81(8), 1562 (1998).

A Measurement of the Appearance of Atmospheric Tau Neutrinos by Super-Kamiokande. The Super-Kamiokande Collaboration, *Phys. Rev. Lett.* 110, 181802 (2013)

Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam, K. Abe et al. The T2K collaboration, Phys. Rev. D 88, 032002 (2013).

Solar Neutrino Results in Super-Kamiokande-III, The Super-Kamiokande Collaboration, K. Abe et al., Phys. Rev. D 83, 052010 (2011).

Search for proton decay via $p \rightarrow vK^+$ using 260 kiloton·year data of Super-Kamiokande ,The Super-Kamiokande Collaboration, PhysRevD.90, 072005 (2014)

First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation, The Super-Kamiokande Collaboration, Phys. Rev. Lett. 112, 091805(2014)

Three flavor neutrino oscillation analysis of atmospheric neutrinos in Super-Kamiokande, The Super-Kamiokande Collaboration, Phys. Rev. D 74, 032002 (2006)

6. Collaboration

a. Institution list

Institute of Cosmic Ray Research, University of Tokyo, University of Tokyo, Gifu University, Kobe University, High Energy Accelerator Research Organization (KEK), IPMU, University of Kyoto, Miyagi University, Nagoya University, Okayama University, Osaka University, Tokai University, Boston University, University of British Columbia, University of California, Irvine, California State University, Dominguez Hills, Chonnam University, Duke University, University of Hawaii, University of Regina, Stony Brook University, Seoul National University, Sungkyunkwan University, University of Toronto, TRIUMF, Tsinghua University, National Center for Nuclear Research, Warsaw, University of Washington, University Autonoma Madrid

- b. Number of present collaborators : 105
- c. Number of collaborators needed.

7. R&D

a. List the topics that will be investigated and that have been completed

Atmospheric neutrinos for: Neutrino oscillation parameters, ν_τ appearance, constraints on sterile, LIV, etc.

Solar neutrinos for: Recoil electron spectrum, MSW evidence, Matter effects in the Earth, oscillation parameters.

WIMP searches from galactic halo and the Sun

Supernova detection and detection of Relic neutrinos from all past supernova

Long Baseline neutrino oscillations as the far detector for T2K

- b. Which of these are crucial to the experiment.
- c. Time line

Super-K is expected to continue to operate until Hyper-Kamiokande begins operation.

- d. Benefit to future projects

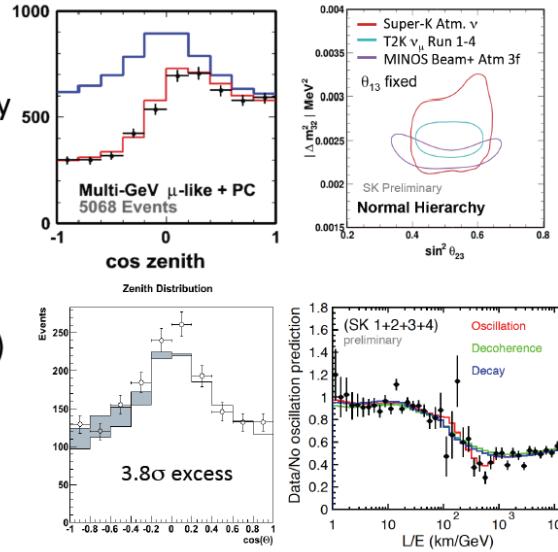
Super- K has developed and continues to develop the techniques that will be necessary for Hyper-K.

8. Primary physics results/sensitivity:

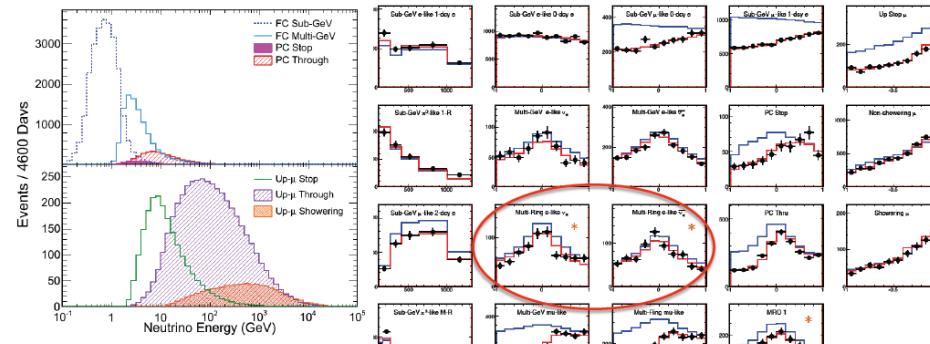
Figures showing the current status and future prospects of the many topics investigated by Super-K

Past Results From Atmospheric ν

- θ_{23} and δm^2_{23} values eventually confirmed by long baseline experiments
- ν_τ appearance
- Oscillation pattern (L/E)
- Constraints on sterile, LIV, etc.



Large Data Sample Allows For Division Into Many Subdivisions

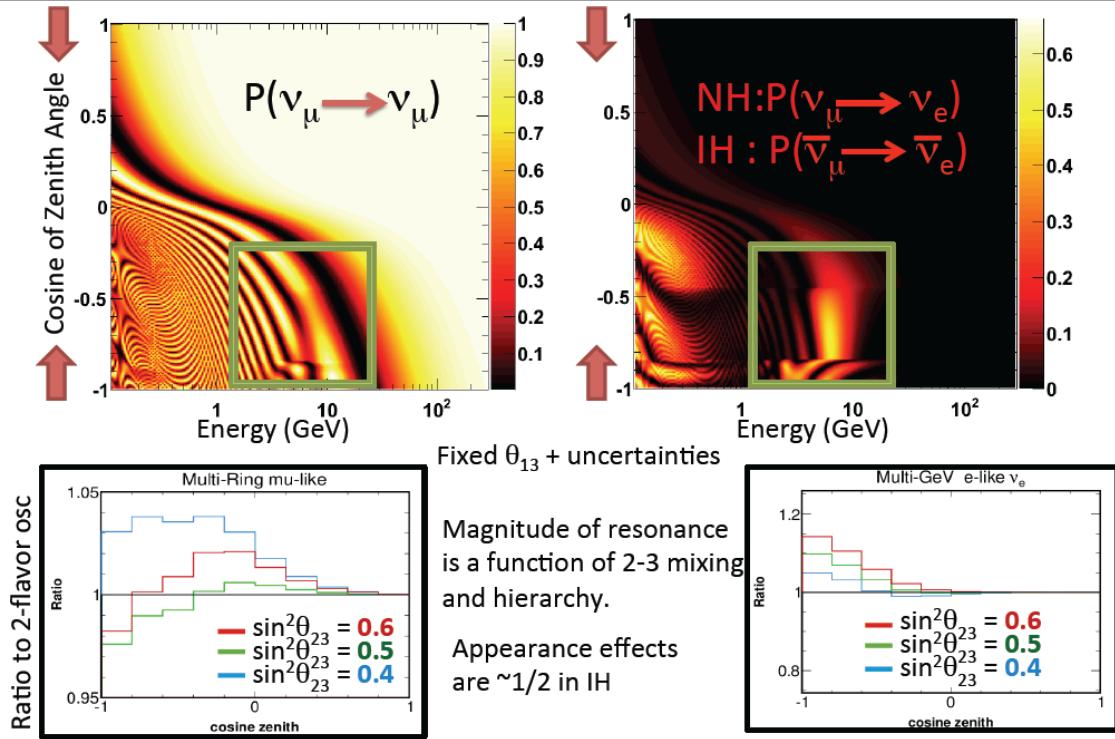


- 19 analysis samples: new multi-GeV e-like samples are divided into ν -like and $\bar{\nu}$ -like subsamples
- Oscillations dominated by $\nu_\mu \rightarrow \nu_\tau$
- Now interested in subdominant contributions to this picture
 - 3-flavor effects
 - Improved Sterile neutrinos
 - Improved Lorentz violation

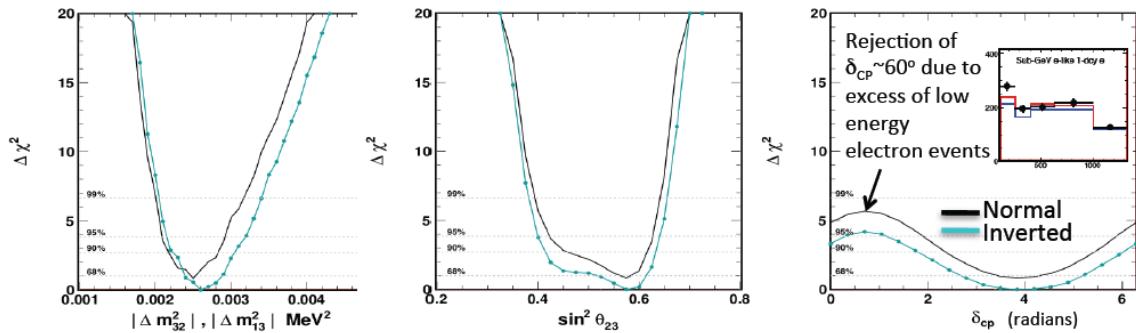
Sensitive to θ_{23} and hierarchy
Multi-Ring e-like Sample Purities

Purity	CC ν_e	CC ν_μ	CC ν_τ	NC
ν -like	69%	7%	11%	11%
$\bar{\nu}$ -like	56%	8%	18%	17%
other	21%	34%	22%	22%

Full 3-Flavor Description of the Oscillations



Super-K Only Analysis With θ_{13} Fixed

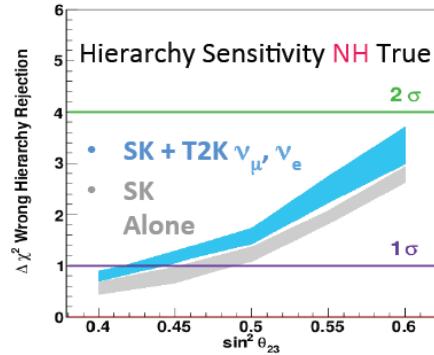
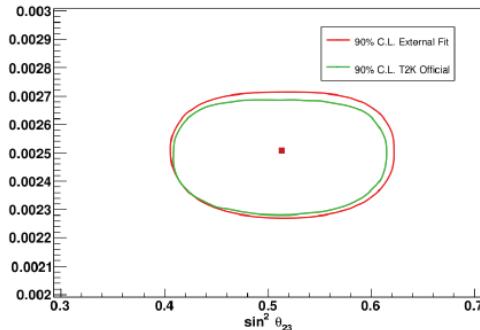


Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23} (\times 10^{-3})$
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84 (220°)	0.57	2.5

Weak preference for normal hierarchy at $\chi^2_{IH} - \chi^2_{NH} = -0.9$

Include T2K With θ_{13} Fixed

Can restrict allowed values of δm^2 and $\sin^2 \theta_{23}$ from T2K data set

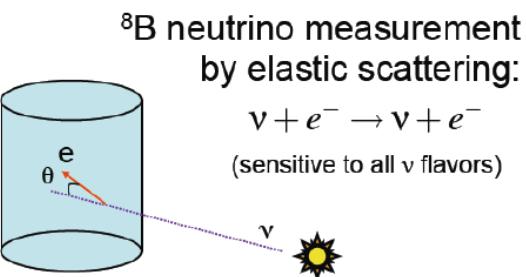
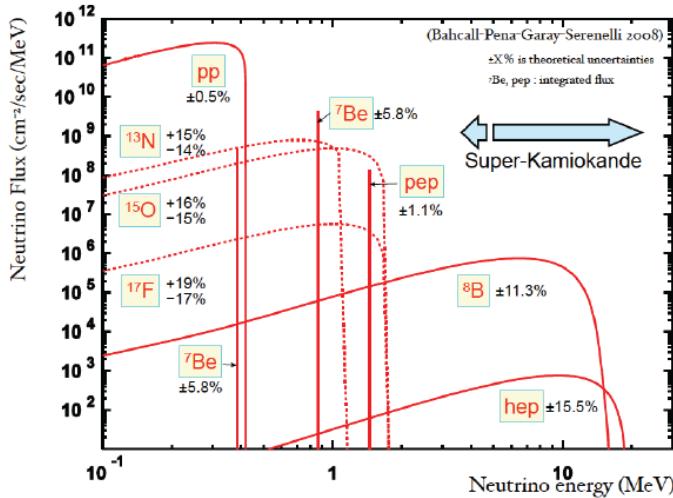


Fit (543 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	$\Delta m_{23} (x10^{-3})$
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

- Normal hierarchy preferred but only at: $\chi^2_{IH} - \chi^2_{NH} = -1.2$ (-0.9 SK only)
- $\sin \delta_{CP} = 0$ allowed at 90% for both NH & IH

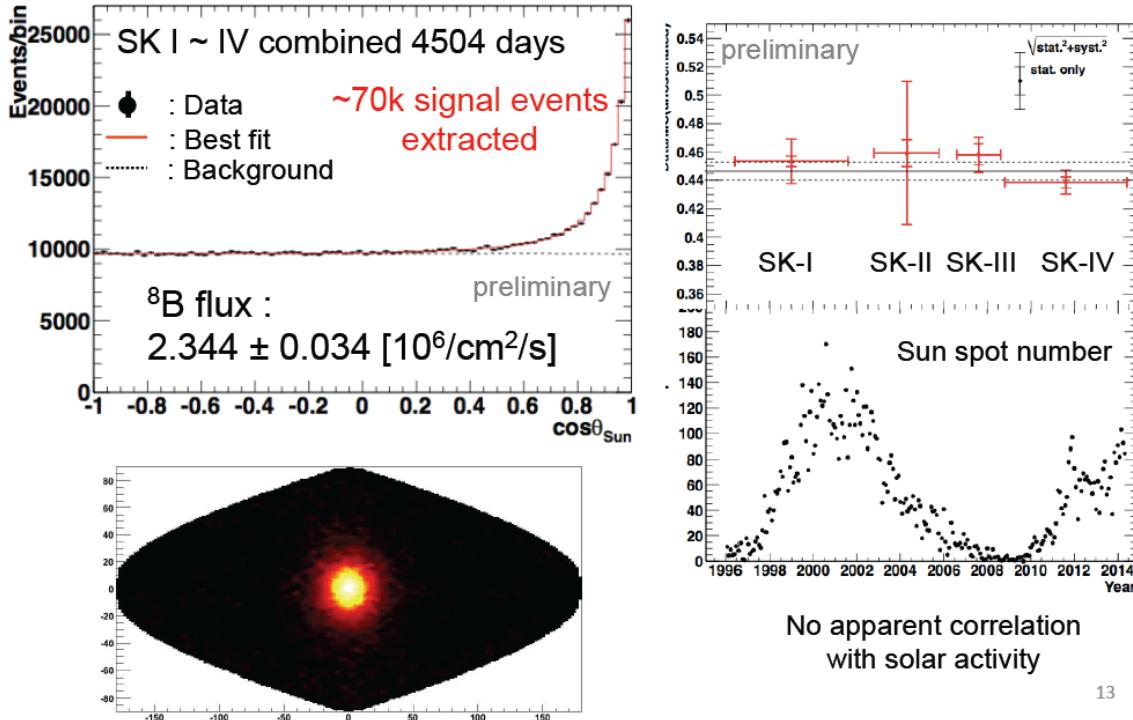
11

SK Solar Neutrinos

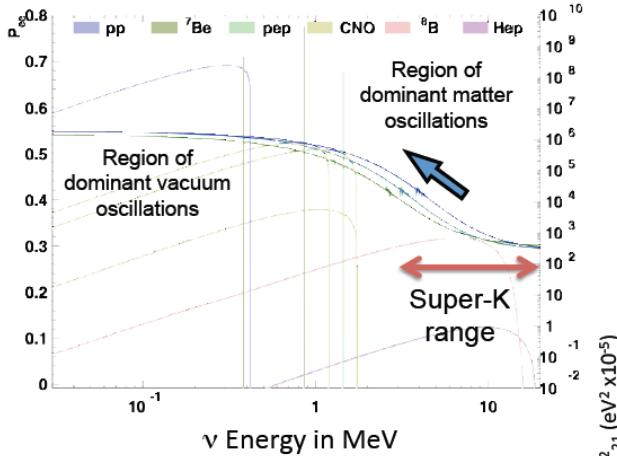


- Flux
- Energy spectrum
- Day/Night flux asymmetry
- Time variation of flux
- Correlation with Solar Activity

Observed Solar Neutrino Signal

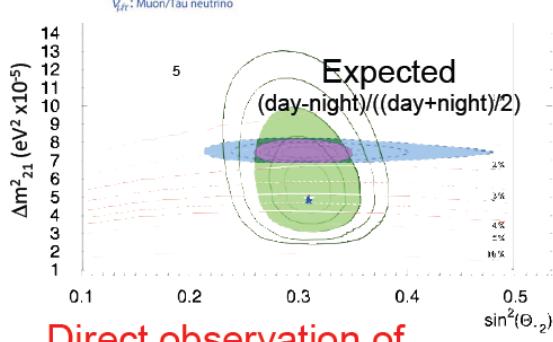
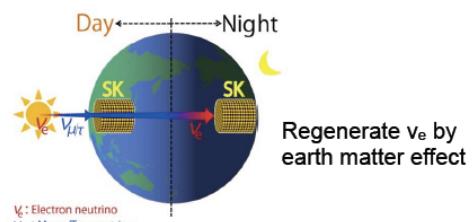


Physics With Solar Neutrinos



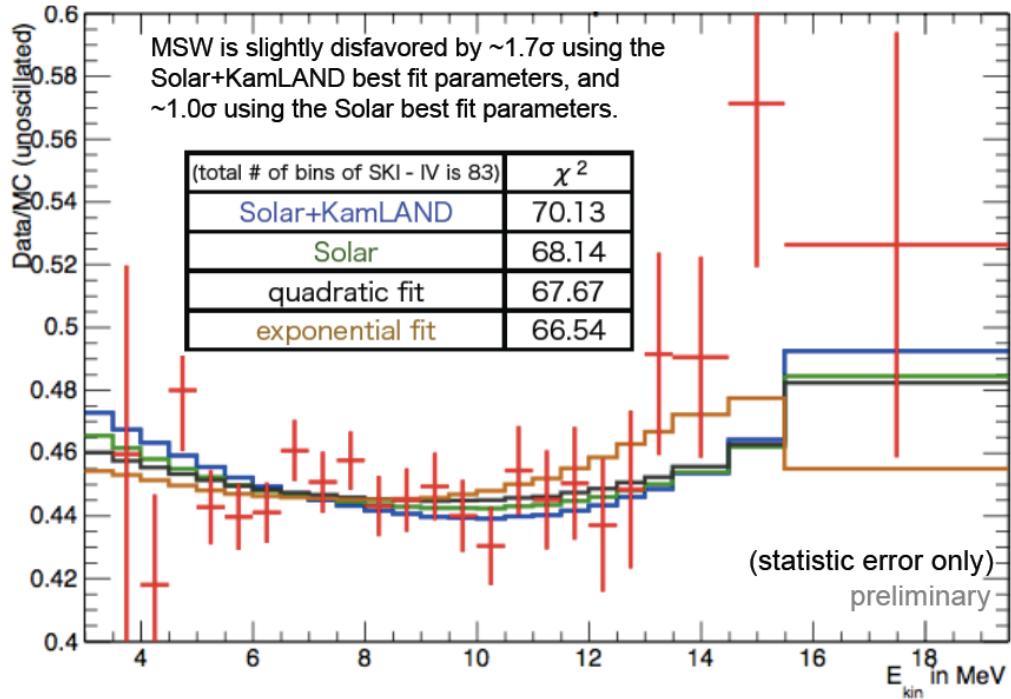
Direct observation of Solar
MSW effect
-Search for spectrum upturn

Day-Night flux asymmetry



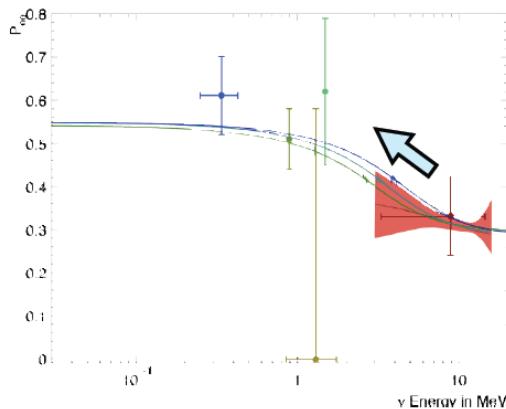
Direct observation of Matter effects in the Earth

Recoil Electron Spectrum



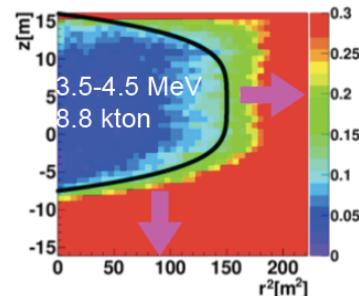
Future Prospects

To see the spectrum “upturn”

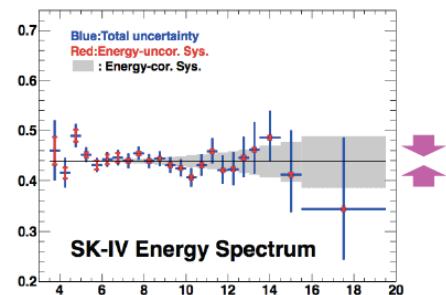


More solar neutrino signal in low energy region -
> new trigger system

✓ Reduce B.G. and enlarge F.V.

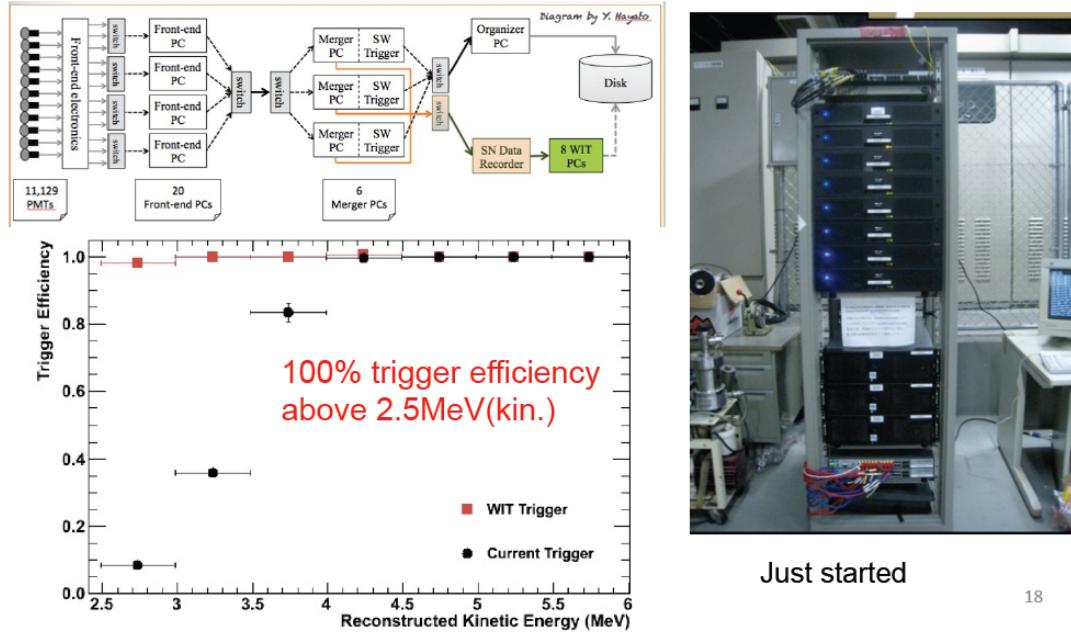


✓ Reduce energy correlated systematic error



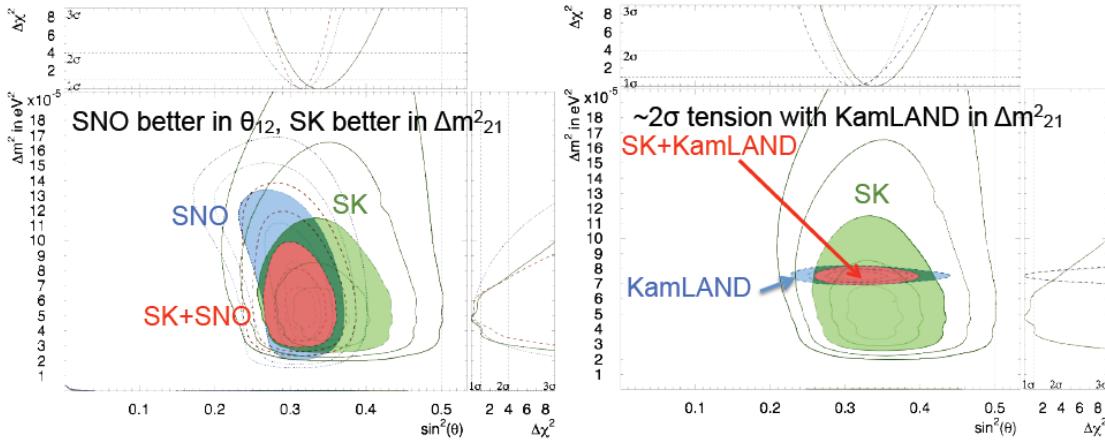
Wide-band Intelligent Trigger (WIT)

Reconstruction and Reduction just after Front-end



Evaluate θ_{12} and Δm^2_{21}

With Reactor constraint: $\sin^2\theta_{13}=0.0242\pm0.0026$



$$\sin^2\theta_{12} = 0.317^{+0.017}_{-0.027}$$

$$\Delta m^2_{21} = 5.4^{+2.2}_{-1.1}$$

$$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$$

$$\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$$

$$\sin^2\theta_{12} = 0.313^{+0.014}_{-0.014}$$

$$\Delta m^2_{21} = 4.86^{+1.4}_{-0.62}$$

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$

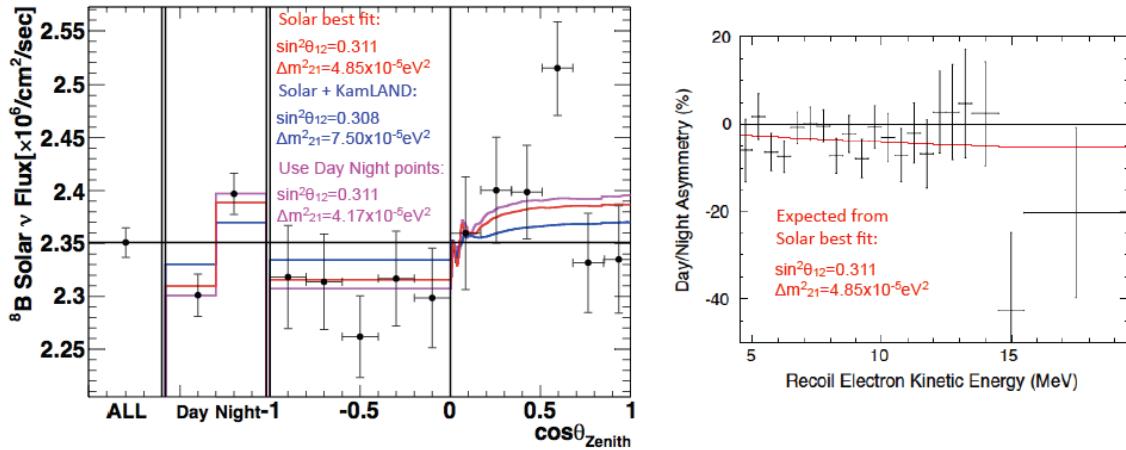
$$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$$

$$\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$$

$$\sin^2\theta_{12} = 0.322^{+0.022}_{-0.019}$$

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17}$$

Zenith Angle & Day/Night



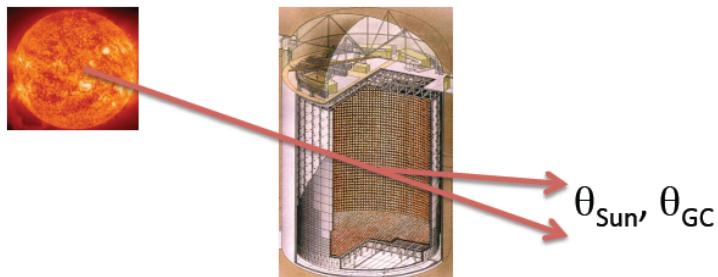
Day/Night asymmetry from matter effects
in the Earth

Day/Night Asymmetry (%) = $-3.3 \pm 1.0 \pm 0.5\%$ ($\sim 3\sigma$ significance)

Phys. Rev. Lett. 112, 091805(2014)

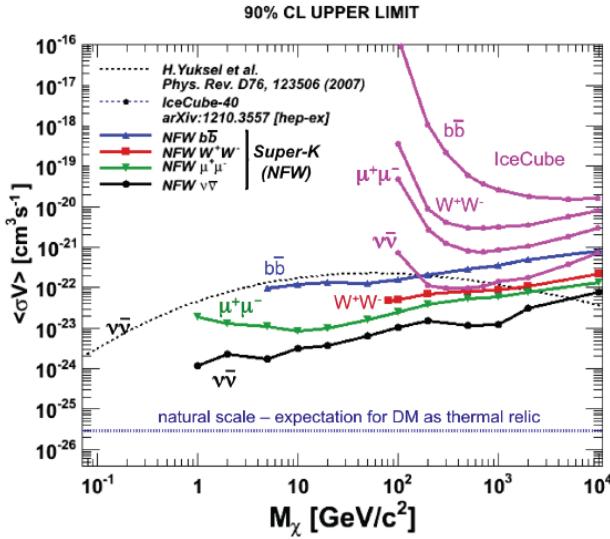
21

Indirect Dark Matter Searches



- Search for directional excess above the atmospheric neutrino background due to WIMP annihilation coming from the center of the Galactic Halo (Beacom, Bell, Mack, PRL 99, 231301 (2007) or the Sun).
- Expected spectra from DARKSUSY
- Assume $\nu\bar{\nu}$, $b\bar{b}$, $t\bar{t}$, W^+W^- branching modes and simulate signal folded with detector response for all ν flavors.

Halo WIMP Limits

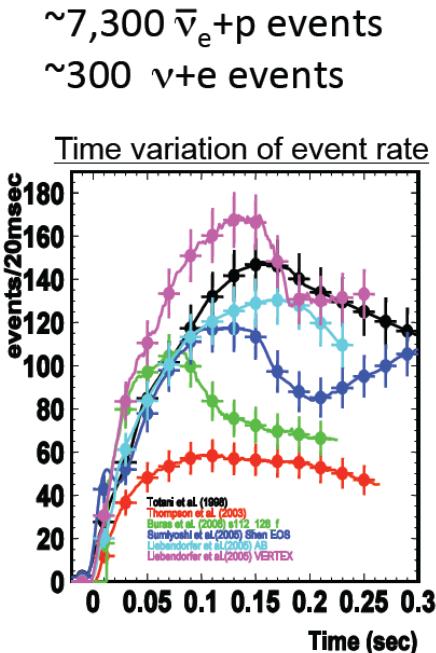


- No evidence for event excess above the atmospheric neutrino background
- Limits placed on the velocity averaged cross section down to WIMP masses of 1 GeV ($\chi\chi \rightarrow \nu\nu$)

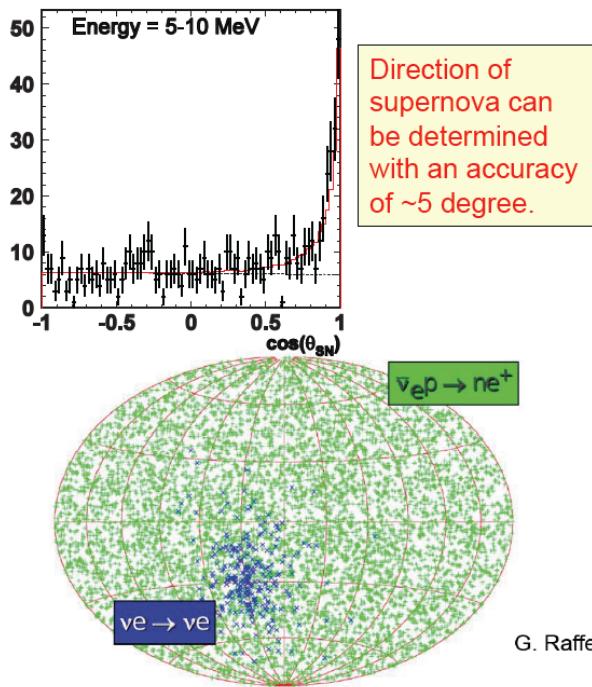
25

SUPERNOVA

Rate in Super-K at 10kpc - 5 MeV Threshold



Discriminate models



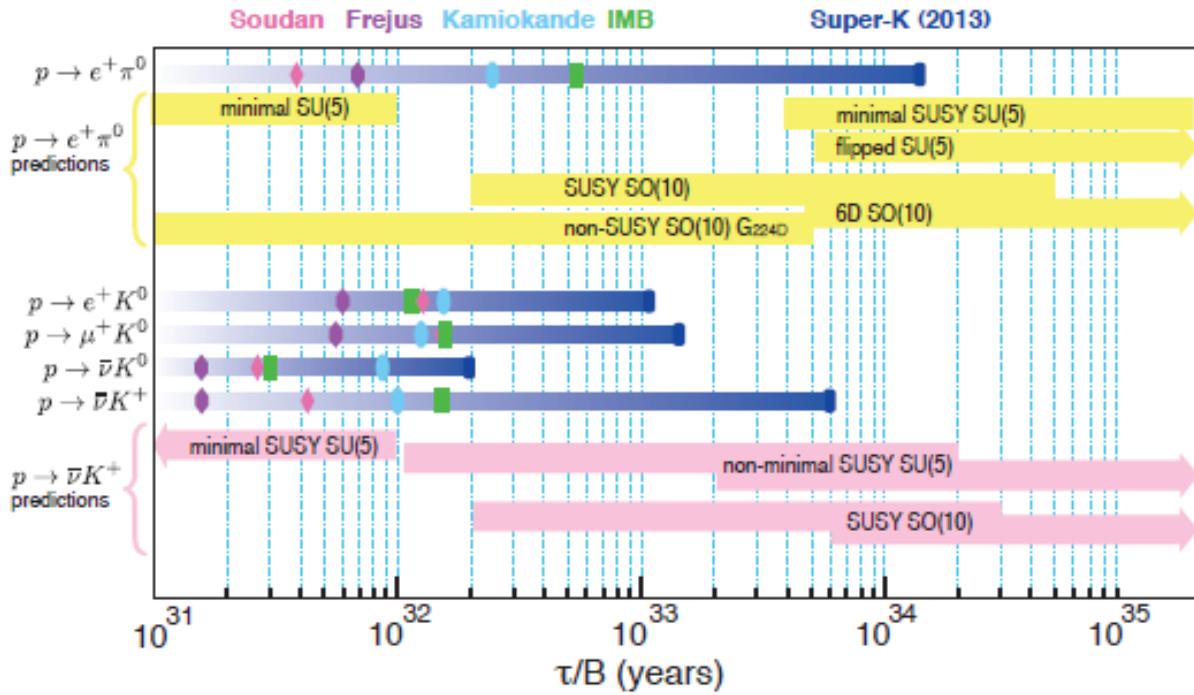
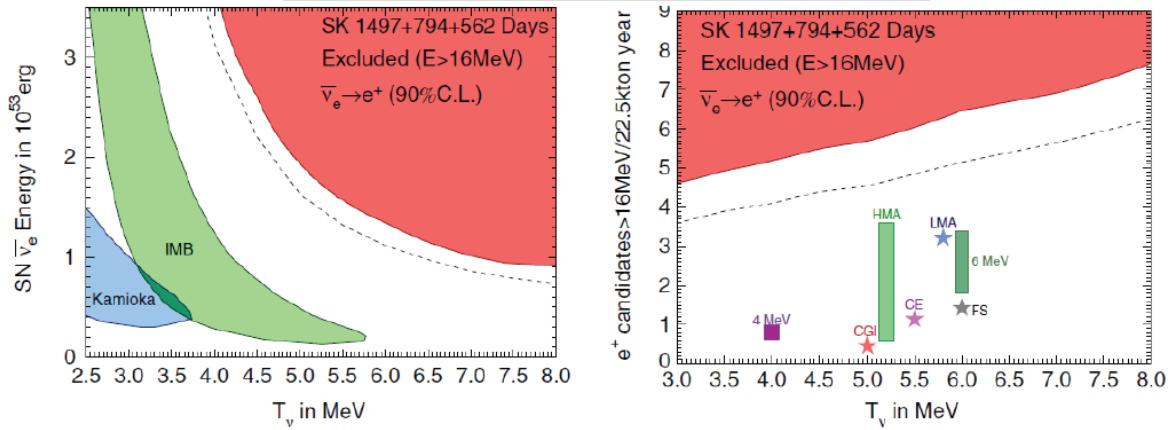
Point with elastic events

28

Supernova Relic Neutrinos

Flux Limits (Phys. Rev. D 85, 052007 (2012))

	Model	SK-I	SK-II	SK-III	All	Predicted
90% C.L. ($\bar{\nu}$ cm $^{-2}$ s $^{-2}$)	Gas infall (97)	<2.1	<7.5	<7.8	<2.8	0.3
$E_\nu > 17.3$ MeV	Chemical (97)	<2.2	<7.2	<7.8	<2.8	0.6
	Heavy metal (00)	<2.2	<7.4	<7.8	<2.8	<1.8
	LMA (03)	<2.5	<7.7	<8.0	<2.9	1.7
	Failed SN (09)	<2.4	<8.0	<8.4	<3.0	0.7
	6MeV (09)	<2.7	<7.4	<8.7	<3.1	1.5



Proton Decay Current Limits

9. Secondary Physics Goal

- a. Expected results/sensitivity
- b. List other experiments that have similar physics goals

10. Experimental requirements – N/A Operating Experiment

11. Expected Experiment/Project time line – N/A Operating Experiment

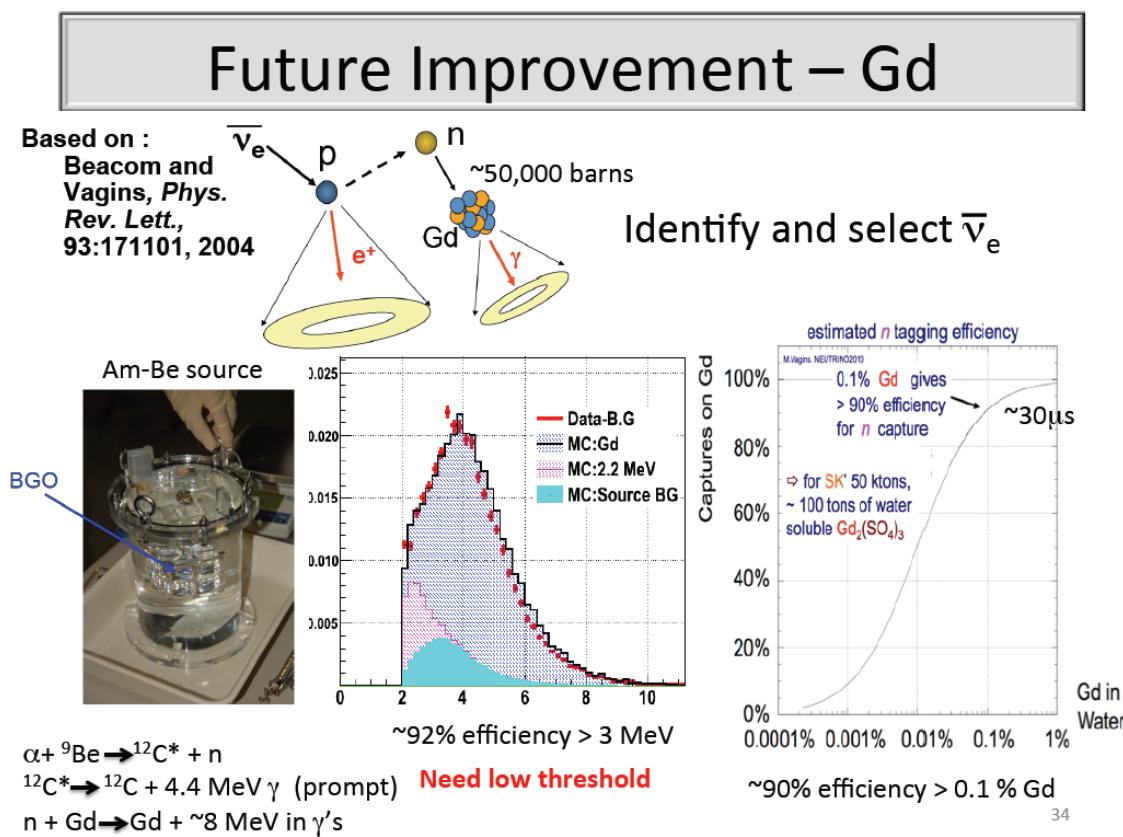
12. Estimated cost range – Operating Experiment

- a. US contribution to the experiment/project – ~5 – 10 M\$
- b. International contribution to the experiment/project - ~100 M\$
- c. US Operations cost - ~0.5 M\$/yr

13. The Future

- a. Possible detector upgrades and their motivation.

We are developing techniques to add Gd ions to Super-K in order to enhance its ability to detect neutrons. Such neutrons are expected from inverse beta decays of low energy anti-neutrinos (such as distant supernova neutrinos or reactor neutrinos). Neutron captures on Gd produce an 8 MeV gamma cascade rather than a 2.2 MeV single gamma (capture on hydrogen) leading to a ~4.5 MeV (equivalent total electron energy) delayed coincidence signal which can be triggered on by a new low energy trigger.



- b. Potential avenues this project could open up.

There are many potential physics benefits, spanning the topics from proton decay to low energy neutrinos, though the most exciting is the dramatic background reduction resulting from efficient neutron tagging in SK for the diffuse, distant supernova neutrinos. This background reduction should make possible the first ever observation of this rare signal.